

Isokinetic strength and endurance tests used pre- and post-spaceflight:

Test-retest reliability

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Authors: Mitzi S. Laughlin¹, Stuart M.C. Lee¹, James A. Loehr¹, William E. Amonette²

Author's Affiliations:

¹Wyle Laboratories, ²Bergalia Engineering

Communicating Author:

Mitzi S. Laughlin, PhD

1290 Hercules, Suite 120

HACD - 261

Houston, TX 77058

(281) 483-2371 office

(281) 483-9676 fax

Mitzi.S.Laughlin@nasa.gov

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Abstract

To assess changes in muscular strength and endurance after microgravity exposure, NASA measures isokinetic strength and endurance across multiple sessions before and after long-duration space flight. Accurate interpretation of pre- and post-flight measures depends upon the reliability of each measure. The purpose of this study was to evaluate the test-retest reliability of the NASA International Space Station (ISS) isokinetic protocol. Twenty-four healthy subjects (12 M/12 F, 32.0 ± 5.6 years) volunteered to participate. Isokinetic knee, ankle, and trunk flexion and extension strength as well as endurance of the knee flexors and extensors were measured using a Cybex NORM isokinetic dynamometer. The first weekly session was considered a familiarization session. Data were collected and analyzed for weeks 2-4. Repeated measures analysis of variance ($\alpha=0.05$) was used to identify weekly differences in isokinetic measures. Test-retest reliability was evaluated by intraclass correlation coefficients (ICC) (3,1). No significant differences were found between weeks in any of the strength measures and the reliability of the strength measures were all considered excellent ($ICC>0.9$), except for concentric ankle dorsi-flexion ($ICC=0.67$). Although a significant difference was noted in weekly endurance measures of knee extension ($p<0.01$), the reliability of endurance measure by week were considered excellent for knee flexion ($ICC=0.97$) and knee extension ($ICC=0.96$). Except for concentric ankle dorsi-flexion, the isokinetic strength and endurance measures are highly reliable when following the NASA ISS protocol. This protocol should allow accurate interpretation isokinetic data even with a small number of crew members.

Keywords: Muscle, microgravity, knee, ankle, trunk, concentric, eccentric

Introduction

The microgravity environment during spaceflight leads to losses of muscle strength and endurance¹⁻⁴. With the construction of the International Space Station (ISS), long duration stays from 4 to 6 months in a 0-g environment have become a regular occurrence. Long duration exposure to microgravity induces larger reductions in muscular function than short duration Space Shuttle missions ranging from 6 to 16 days⁴⁻⁶. This reduction in muscle function can pose potential problems when returning to the 1-g Earth environment or during exploration class missions to the Moon or Mars.

To evaluate the effectiveness of in-flight countermeasures as well as document the progress of rehabilitation programs upon returning from long duration missions, isokinetic muscle strength and endurance are measured during repeat sessions in US crewmembers both pre- and post-flight. A standard pre- and post- flight protocol was developed to measure the strength and endurance of all US long-duration crewmembers utilizing a Cybex NORM (CSMI, Inc.; Stoughton, MA) isokinetic dynamometer. The NASA ISS isokinetic protocol measures concentric flexion and extension strength of the knee, ankle, and trunk, eccentric flexion and extension strength of the ankle, as well as flexion and extension endurance of the knee. Trunk and lower extremity muscles were targeted because of the high potential for losses due to microgravity exposure.

Since accurate countermeasure evaluation and rehabilitation success depends on standard muscular performance measures, it is necessary to document the test-retest reliability of the NASA isokinetic protocol. Previously, the reliability and validity of strength tests conducted on isokinetic dynamometers have been shown to be good to excellent⁷⁻¹³ but no published protocol mimics the measures of the NASA ISS isokinetic protocol. We expect that our results will be

similar to other published papers, but because of the small number of long-duration crewmembers and the importance of countermeasure evaluation for NASA's goal of exploration, it is essential to know the reliability of each specific measure. Therefore, the purpose of this study was to evaluate the test-retest reliability of the NASA specific ISS isokinetic protocol.

Methods

Subjects

Twelve male and 12 female subjects (32.0 ± 5.6 years, 172.0 ± 9.9 cm, 73.5 ± 12.3 kg) volunteered to participate in this evaluation. All subjects were considered healthy and passed a modified Air Force Class III physical prior to participating. The study protocol was approved in advance by the NASA-JSC Committee for the Protection of Human Subjects. Each subject provided written informed consent before participating.

Protocol

Subjects reported to the laboratory approximately once per week for four weeks. Isokinetic data were collected using a Cybex NORM isokinetic dynamometer. The NASA ISS protocol assessed concentric strength of the knee, ankle, and trunk as well as eccentric strength of the ankle. Additionally, the protocol measured concentric endurance of the knee musculature (Table I). This protocol was designed to be performed in a limited amount of time due to crew schedule constraints, therefore not all types of testing are performed at all joints. The right limb was used for all lower extremity measures. The dynamometer was calibrated per manufacturer's protocol on each day of data collection and the subject was positioned according to the Cybex instruction manual¹⁴ except when noted.

[Insert Table I here]

Upon arrival to each laboratory session, subjects completed a brief diet and activity questionnaire and performed a 5-minute warm-up on a cycle ergometer at approximately 50 Watts with a cadence of 70 revolutions per minute. Subjects were instructed to stretch the corresponding musculature before being positioned for each test. Positioning of the subject during the familiarization session was recorded so that it could be reproduced across each session. The same test operators were maintained across all sessions for a given subject. Standard joint specific warm-up procedures were followed and consisted of 5 submaximal repetitions and 3 maximal repetitions utilizing actual testing movements and speeds. After the specific joint movement and speed warm-up, data collection began following at least 2 minutes of rest.

The first strength test, knee extension and flexion, was conducted in the seated position. Knee range of motion (ROM) was set from 20 deg to 95 deg for both the knee strength and endurance measures. Measures for gravity correction were taken to reduce the effect of limb weight on torque production. Data collection began with 5 maximal concentric knee extension repetitions at 60 degrees per second. At the end of each repetition the subject was instructed to relax and the test operator moved the limb back to the starting position. After completion of all 5 knee extension repetitions, 5 maximal concentric knee flexion repetitions were performed. Following the knee strength tests, the speed of the test was changed to 180 degrees/sec for the knee endurance test. Unlike the knee strength tests, the endurance test was performed as 21 continuous repetitions of knee extension and flexion. Subjects were instructed to perform two to three submaximal repetitions to familiarize themselves to the faster speed which was followed by 2 minutes of rest. The knee endurance test consisted of 21 repetitions at 180 degrees/sec.

The second test was ankle plantar and dorsi-flexion conducted in the prone position. A standard athletic shoe was used for all of the ankle tests to eliminate the potential variability in measures due to footwear. Additional straps were used to help secure the subject during the ankle testing. The first additional strap was placed around the ankle and footplate in a figure 8 pattern to help keep the heel against the footplate (Figure 1). In order to prevent the subject from sliding along the bench and lifting the hips with ankle movement, two straps were added to secure the subject to the bench. The two straps were placed in a crossing pattern on the bench and secured to the hand grips. After the subject was positioned on top of the straps in a prone position, the two straps were then brought over the subject's shoulders and crossed along the subject's back (Figure 2). The shoulder straps were snug and prevented sliding along the bench, but did not cross too high on the body and rub on the neck. Finally, the Cybex seat belt was then secured across the subject's hips to prevent the hips from lifting off the bench during testing.

[Insert Figures 1 & 2 here]

Ankle ROM was set to the subject's maximum plantar and dorsi-flexion or a minimum of 15° dorsi-flexion and 30° plantar-flexion. After the standard joint specific warm-up and 2 minutes of rest, data collection began with 5 maximal concentric plantar flexion repetitions at 30 degrees per second. At the end of each repetition, subjects were instructed to relax and the ankle was returned to the starting position. After completion of the plantar flexion repetitions, subjects performed 5 concentric maximal dorsi-flexion repetitions at 30 degrees/sec. Each subject also performed an eccentric ankle dorsi-flexion and plantar flexion strength test. The eccentric strength test followed the same protocol as the concentric ankle test, but the subject was instructed to perform an isometric muscle contraction just prior to the dynamometer moving.

The final test consisted of trunk flexion and extension performed with the Trunk Modular Component adapter (CSMI, Inc.; Stoughton, MA) for the Cybex NORM. ROM was set from 0 deg extension to 90 deg flexion. Following the standard joint specific warm-up and 2 minutes of rest, each subject performed 5 maximal concentric trunk flexion reps at 60 degrees/sec. At the conclusion of each repetition, the subject was instructed to relax and was moved back to the starting position. The subject then performed 5 concentric maximal trunk extension reps at 60 degrees/sec.

Statistical Analysis

The first week was a familiarization session in which the subjects completed the entire protocol but the data were not used for analysis. Peak torque and total work data were analyzed from weeks 2 thru 4. Peak torque was defined as the highest torque produced during a repetition. Peak torque was recorded for every repetition and the highest weekly value was considered the peak torque for the session. This resulted in 3 measures, one for each weekly session, for each of the strength tests. For the knee endurance test, extension and flexion total work measures were calculated for each week of testing. Total work was calculated as the sum of work performed during repetitions 2 through 21 of the knee endurance test. The first repetition was excluded, since the repetition was often a submaximal effort. Knee extension and flexion total work were calculated separately.

Means and standard deviations were calculated for all strength and endurance measures for each week of testing. Repeated measures analysis of variance (ANOVA) was used to determine if there were any week to week differences in strength and endurance measures. To establish test re-test reliability, intraclass correlation coefficients (ICC) (3,1) were computed for

strength and endurance measures. The standard error of measurement (SEM) was calculated as an additional measure of accuracy for each strength and endurance test [$SEM = SD \cdot (1 - ICC)^{0.5}$].

Results

Weekly peak torque means and standard deviations for all strength measures are given in Table II. No significant differences were found between weeks in any of the strength measures ($p > 0.05$). The reliability of the strength measures by week were all considered excellent ($ICC > 0.9$) except for the concentric measure of ankle dorsi-flexion ($ICC = 0.67$). The SEM was less than ± 10.6 Nm per strength measure and represented from 2.6% to 4.7% of the mean score except for the concentric ankle dorsi-flexion which was 2.8 Nm or 9.2%.

[Insert Table II here]

The total work means and standard deviations for knee endurance tests are shown in Table III. A significant difference was found between weekly measures of knee extension endurance ($p < 0.01$). Total work for knee extension improved approximately 55 Nm between each week of testing. Although the knee extension measures increased each week, the reliability was considered excellent ($ICC = 0.97$). No significant differences were noted for endurance measures of knee flexion ($p = 0.96$). The reliability of the endurance measures by week were considered excellent for knee flexion ($ICC = 0.96$). The total work SEM was ± 56.9 Nm per endurance measure which represented from 2.9% to 3.5% of the mean total work score.

[Insert Table III here]

Discussion

The ISS isokinetic protocol was chosen to maximize the amount of information gathered about different muscle groups and types of contractions in a minimum amount of time. Specifically, the time allotted to perform any medical test is limited by the amount of training required to prepare for space flight missions, especially at critical times for training and data collection as the launch time approaches. Testing efficiency also is paramount in the post-flight recovery period when many medical tests and science investigations are scheduled so as to determine the health of the crewmembers and to understand the physiologic adaptations that have occurred during the course of the mission. These tests compete for the crewmember's time with each other and with mission debrief activities at a period when the crewmember may be fatigued, needs time with family and friends after a long separation, and is participating in an active rehabilitation program.

Although many different isokinetic protocols have been used in clinical and research settings, the ISS protocol is specific to the joints and muscles most affected during long duration spaceflight. The ISS protocol focuses on the major muscle groups which are anticipated to be affected by space flight^{5,15}. Specifically, the extensor and flexor muscles of the leg, lower leg, and trunk were chosen since they represent many of the muscle groups involved in posture and ambulation in normal gravity. Although much attention has been placed upon the extensor muscles in short duration missions, as the length of the unloading time increases muscle atrophy and decreased performance also are apparent in the flexors. Further, the testing includes concentric strength, eccentric strength, and muscle endurance aspects because of their roles in activities of daily living as well as mission critical tasks; future testing protocols also may include an isometric component. Tests are not conducted bilaterally nor are each muscle group due to time constraints, and therefore the protocol was designed to provide a snapshot of overall

muscle performance. As such, this protocol has been accepted as a standard measure in NASA's testing of space flight participants and bed rest subjects, an analog of space flight.

Isokinetic strength and endurance measures are important not only to NASA to understand countermeasures but also to external investigators who are allotted a small number of subjects for their studies. The number of ISS crew members will always be considered small when compared to similar ground-based studies, so it is paramount that ISS protocols are reliable. Likewise an individual's measure must be accurately interpreted to determine if differences between testing sessions are true differences in muscular performance or due to measurement error. This is accomplished by calculating the standard error of measurement (SEM) and determining a 95% confidence interval around the score.

In this study, the reliability of knee strength measures were considered excellent for extension (ICC=0.97) and flexion (ICC=0.95) over the three weeks of testing. These results are similar to other published studies⁹⁻¹³, but few studies have interpreted individual measures by calculating the SEM. The SEM for the knee strength tests were 5.3 Nm (3.0%) for extension and 3.7 Nm (3.7%) for flexion. Therefore, if an individual's knee extension strength differs by more or less than 10.6 Nm or 6.0% for the mean strength score between testing sessions, we can be 95% confident that the difference is due to strength changes rather than measurement error. Similarly, if a knee flexion strength measure differs by ± 7.4 Nm (7.4%) then the difference is likely due to changes in muscular strength.

The reliability of the knee endurance measures were considered excellent for both knee extension (ICC=0.96) and flexion (ICC=0.98), although there were significant differences found between weekly measures of knee extension. Each week endurance measures for knee extension improved approximately 55 Nm or 3% while no significant differences were noted in knee

flexion. Although no true peak score was achieved, reliability coefficients remained high for knee extension because all subjects improved at the same relative rate regardless of initial knee endurance score. The SEM for knee endurance was 56.1 Nm (or 2.9% for the mean strength measure) for extension and 42.2 Nm (3.5%) for flexion. We can be 95% confident that differences between endurance testing sessions are not measurement error if scores differ by at least 5.8% for extension and 7.0% for flexion.

Reliability results from ankle strength tests are somewhat mixed in the literature^{8,16-18} and our result also followed this trend. For concentric ankle strength, Holmback et al showed excellent results in a study that only tested ankle dorsi-flexion (ICC=0.93)⁷, and Woodson et al reported good reliability for plantar-flexion (ICC=0.80) and dorsi-flexion (ICC=0.88)⁸. Woodson noted that their reliability coefficients were lower than the reported literature and could be due having a low number of subjects participate in the study. In our study, concentric ankle plantar-flexion strength measures were highly reliable (ICC=0.93) with a corresponding low measurement error (SEM=5.2 Nm or 4.3% for the average strength score). However, reliability of concentric ankle dorsi-flexion was considered low (ICC=0.67) and the percentage of measurement error was unacceptable (SEM=2.8 Nm or 9.2% for the average strength score). An ankle dorsi-flexion measurement would have to differ by $\pm 18.4\%$ to be 95% confident that the difference was due to strength changes rather than measurement error. The low reliability and corresponding high measurement error is possibly due to the lack of variability in ankle dorsi-flexion strength between subjects.

Few data exist in the literature focusing on the reliability of eccentric ankle strength measures. Over the three weeks of testing, the reliability of eccentric ankle strength measures were considered excellent for plantar-flexion (ICC=0.93) and dorsi-flexion (ICC=0.96). The

SEM for the eccentric ankle strength tests were 7.1 Nm (4.7% of the mean score) for plantar-flexion and 1.2 Nm (2.6% of the mean score) for dorsi-flexion. In this study the eccentric reliability measures are excellent, and are probably due to strict adherence to the standardized protocol. Subjects are generally unfamiliar with this type of eccentric exercise and this can adversely affect reliability measures ¹⁶ and many researchers suggest a familiarization period prior to testing in order to increase reliability ^{16,19,20}. In our study, the subjects performed the entire ISS isokinetic protocol as a familiarization session 1 week prior to starting data collection to enable the subject to adjust to the testing movements and speeds. Additionally, a standard joint specific warm-up was performed just prior to data collection to allow our subjects to adjust to the specific movements and speeds required during testing. The combination of the familiarization session and standard warm-up most likely influenced the results of this study and allowed us to obtain excellent eccentric reliability measures.

The final strength test in the ISS isokinetic protocol tested the trunk. Reliability of trunk flexion (ICC=0.96) and extension (ICC=0.96) were both excellent, while the SEM were low for flexion (SEM=7.1 Nm or 3.2% of the mean strength score) and extension (SEM=10.6 Nm or 4.2% of the mean strength score). Previously Karatas et al showed excellent reliability (ICC>0.95) on the Cybex Norm for trunk flexion and extension ²¹, and Wessel et al only tested trunk flexion but obtained similar results (ICC=0.93 and SEM=18.0 Nm) ²² on a KinCom (Chattecx; Chattanooga, TN) dynamometer.

The utility of any assessment method depends upon the knowledge of, and ability to control, factors that influence the measurements ⁷. Several potential sources of error in the ISS isokinetic protocol were recognized and the effects reduced to optimize reliability prior to data collection. First, the Cybex NORM isokinetic dynamometer was calibrated according to the

manufacturer's protocol on each day of testing. Subject familiarization with the equipment was deemed necessary, and a familiarization session was performed prior to the first data collection session. During this session subjects performed the entire ISS protocol but the data was not used for analysis. Also, the warm-up procedures before each test session followed a strictly standardized protocol that included a general warm up on a cycle ergometer and then movement specific warm-up repetitions prior to testing. Both the number of warm-up repetitions and the intensity were standardized in the ISS protocol to obtain consistent results. Data collection was also strictly standardized which included the instructions to subjects and the amount of encouragement given during data collection.

One of the most important factors affecting isokinetic testing reliability is stabilization of the tested limb and the subject. The use of supplementary muscles is possible and may affect the reproducibility of the data. Andersen found that a 1.5 cm displacement of the anatomic axis of the ankle joint could account for a 10% change in dorsi-flexion and plantar flexion peak torque¹⁷. Our previous experience with prone ankle testing showed that subject stabilization was poor and frequently the heel lifted from the foot plate, hips lifted from the bench, and the subject would move upward along the bench with the ankle movement. To counteract these issues, four additional straps/belts were added to the ankle setup to secure the heel to the footplate and secure the subject to the bench. After the subject was positioned correctly, the lever arm, belts and seat position were recorded for future testing sessions to minimize this potential source of error.

The time between testing sessions has also shown to affect reliability⁷. The shortest reported time was 10 minutes in a study that showed low reliability as measured using Pearson correlations ($r=0.67$ to 0.79)²³. One to 7 days between testing sessions are more common and generally find higher reliability results than same day retesting⁷. To ensure that the effects of

learning and fatigue were eliminated in our study, the testing sessions were separated by approximately 7 days.

Although the present study provides valuable information, there are limitations to this study. Data were collected on a weekly basis in this study, whereas actual pre- to post-flight data collection sessions may be separated by many months. Normally isokinetic testing is preformed twice pre-flight, at approximately 6 months and again 1 to 1.5 months before launch. Post-flight testing occurs at approximately 6 (no trunk testing), 15, and 30 days after landing. Also it is important to note no attempt was made to evaluate the clinical usefulness of isokinetic measurements in the present study.

The purpose of this study was to examine the reliability of the isokinetic testing protocol used to evaluate strength and endurance for US ISS crew members. We have demonstrated that the ISS isokinetic strength and endurance protocol can be conducted with highly reliable results and low measurement errors, except for concentric ankle dorsi-flexion. Since ankle dorsi-flexor strength may change during long-duration space flight, further testing should be performed to determine if there is a more reliable way to test the ankle dorsi-flexors.

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Table I. NASA ISS Isokinetic Protocol

Joint Motion	Contraction	Speed	ROM	Repetitions
Knee Extension	Concentric	60°/sec	20 to 95°	5
Knee Flexion	Concentric	60°/sec	20 to 95°	5
Knee Ext. & Flex.	Concentric	180°/sec	20 to 95°	21
Ankle Plantar Flexion	Concentric	30°/sec	subject max or -15 to +30°	5
Ankle Dorsi Flexion	Concentric	30°/sec	subject max or -15 to +30°	5
Ankle Plantar Flexion	Eccentric	30°/sec	subject max or -15 to +30°	5
Ankle Dorsi Flexion	Eccentric	30°/sec	subject max or -15 to +30°	5
Trunk Flexion	Concentric	60°/sec	0 to 90°	5
Trunk Extension	Concentric	60°/sec	0 to 90°	5

Table II. Means (\pm SD) for all strength measures

Joint Motion	Week 2	Week 3	Week 4	p	ICC (3,1)	SEM (%)
Knee Extension	177.6 \pm 55.7	173.8 \pm 54.8	178.2 \pm 55.9	0.215	0.973	5.3 (3.0%)
Knee Flexion	100.5 \pm 29.7	101.4 \pm 29.6	101.0 \pm 30.6	0.887	0.954	3.7 (3.7%)
Ankle PF Con	121.6 \pm 28.7	120.8 \pm 32.4	125.8 \pm 35.5	0.124	0.925	5.2 (4.3%)
Ankle DF Con	31.6 \pm 9.9	30.0 \pm 6.1	30.8 \pm 5.8	0.429	0.666	2.8 (9.2%)
Ankle PF Ecc	147.8 \pm 43.7	154.7 \pm 44.9	157.1 \pm 51.0	0.079	0.932	7.1 (4.7%)
Ankle DF Ecc	45.7 \pm 9.4	46.8 \pm 10.4	46.8 \pm 9.6	0.083	0.960	1.2 (2.6%)
Trunk Flexion	220.5 \pm 61.4	222.9 \pm 62.9	224.4 \pm 66.3	0.534	0.963	7.1 (3.2%)
Trunk Extension	251.6 \pm 66.3	252.6 \pm 104.1	244.0 \pm 88.9	0.222	0.963	10.6 (4.2%)

Table III. Means (\pm SD) for knee endurance measures (total work)

Joint Motion	Week 2	Week 3	Week 4	p	ICC (3,1)	SEM (%)
Knee Extension	1907.6 \pm 630.4	1964.6 \pm 634.5	2017.4 \pm 653.5	0.001	0.977	56.1 (2.9%)
Knee Flexion	1172.8 \pm 381.0	1214.8 \pm 362.0	1214.8 \pm 385.0	0.081	0.962	42.2 (3.5%)

Figure 1a. Cybex straps securing foot in footplate during ankle testing.

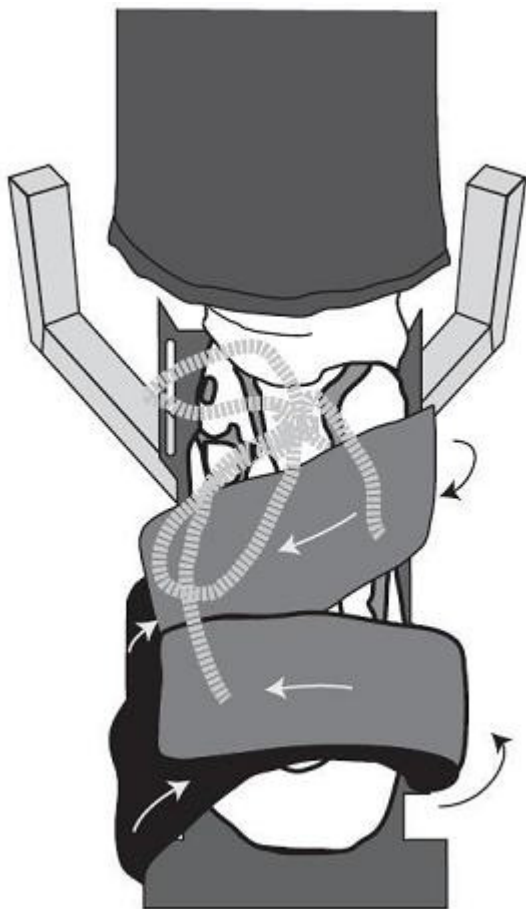


Figure 1b. Additional figure 8 strap to secure heel to footplate during ankle testing.

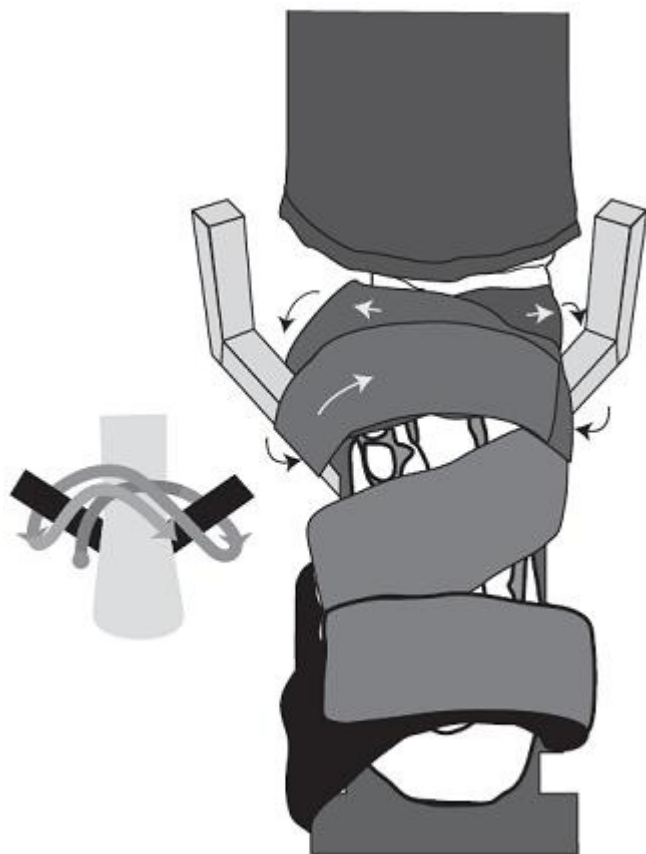


Figure 2. Shoulder and hip straps for ankle testing.

